Helicity amplitudes analysis

S. Bhawani, Harut Avakian (JLab)

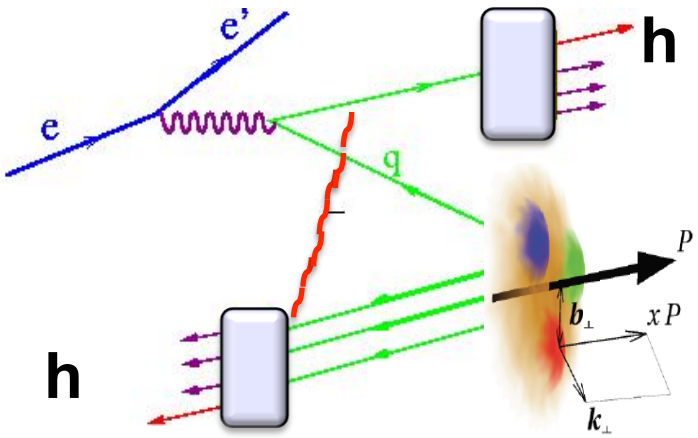
CLAS12 Collaboration Meeting, Nov 18, 2026

- Exclusive hadron production from longitudinal and transverse photons
- Updating experimental extraction procedures
- Updating the analysis framework
  - •from structure functions→helicity structure functions→helicity amplitudes
  - •from bin-based analysis to event-based analysis
- Critical role of MC simulations(precise exclusive MC most critical for SIDIS and vice versa)
- Summary

3D PDFs: Hadron production in electroproduction

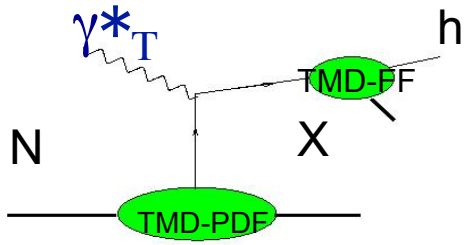
$x_F>0$

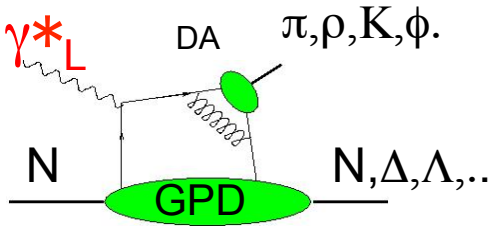
Current Fragmentation Region (CFR)

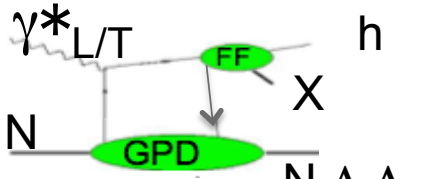


Target Fragmentation Region (TFR)

$x_F<0$







Semi-exclusive production (Guo-Yuan)

Study

x,Q^2,z,P_T,ϕ,ϕ_S $\sim 1/Q^4$

Flavor and polarization dependence of transverse momentum distributions

$x,Q^2,t,\phi,\phi_S+\phi,\theta$ $\sim 1/Q^6$

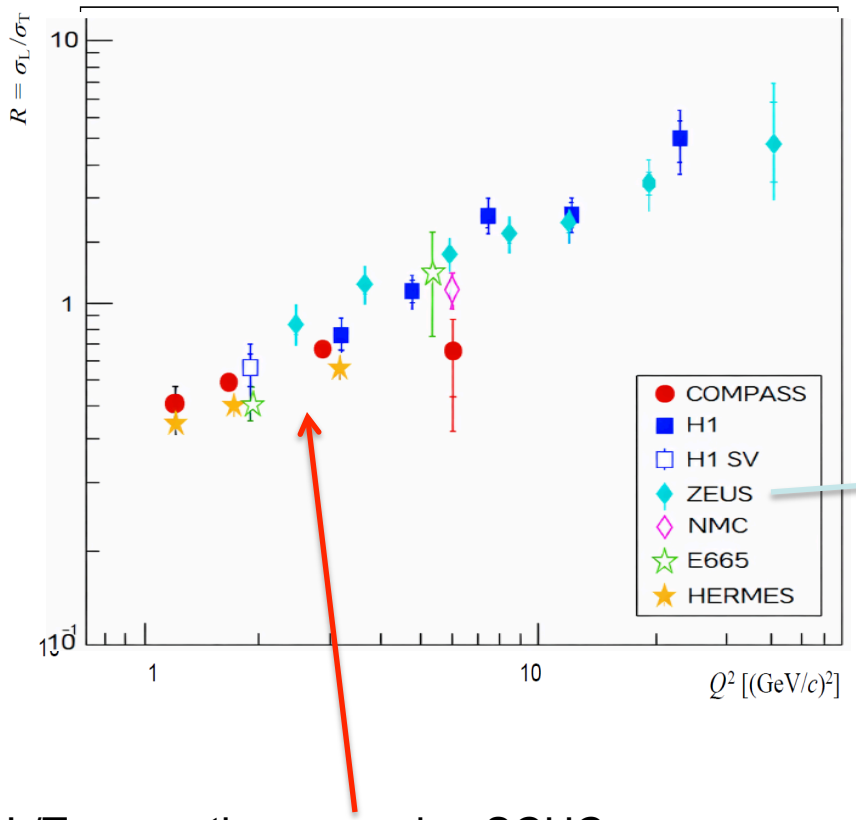
Flavor and polarization dependence of transverse space distributions

Factorization proved for longitudinal photons

correlations and entanglement of CFR and TFR, controlling CFR, allowing access to GPDs and GTMDs

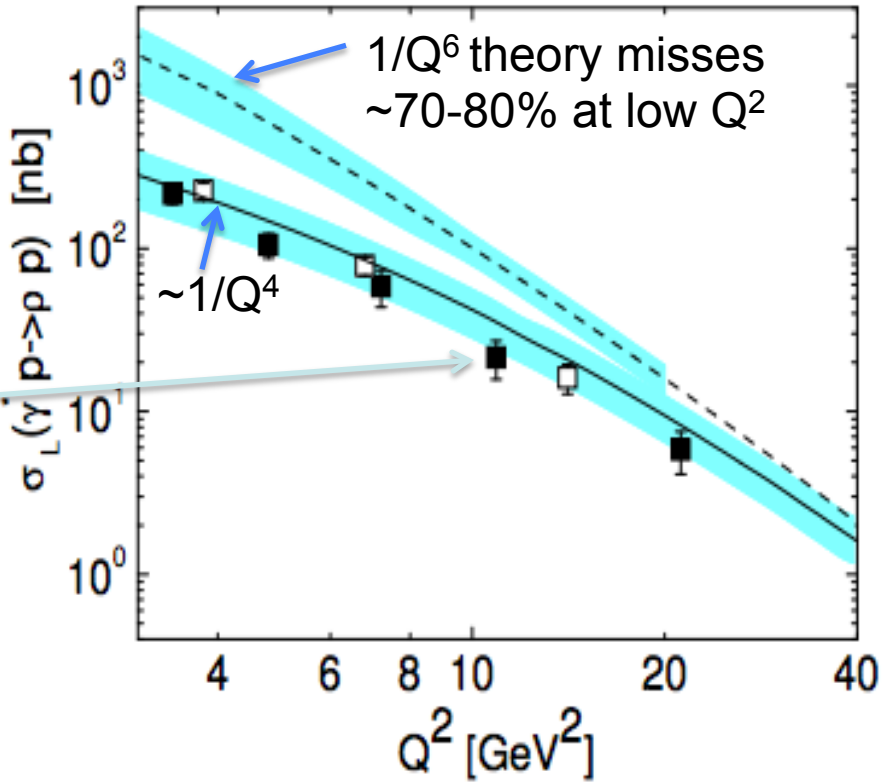
- Different non-perturbative objects may be involved with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

Separating Longitudinal photon contributions



L/T separation assuming SCHC (helicity conservation)

"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge." D.J. Boorstin



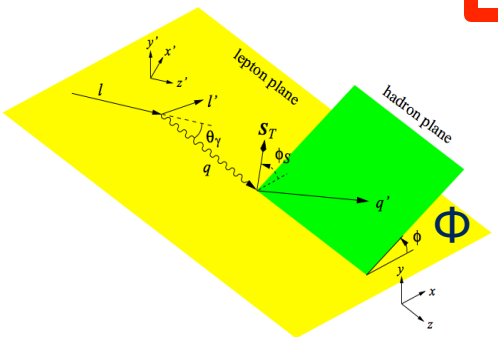
The ZEUS measurements, followed by others, indicated that the longitudinal photon contributions (diffractive rho) drop as ~1/Q^4 → dramatically underestimate low Q^2 ρ^0s

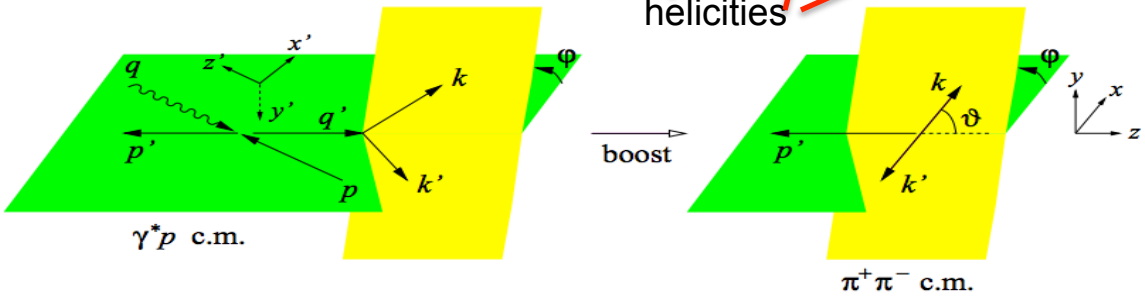
To be checked both, extraction of σ_L cross-section and evaluation of σ_L/σ_T

Kinematics of VM production

Diehl: 0704.1565 $T^{\nu\sigma}_{\mu\lambda}$ helicity amplitudes describing $\gamma^*(\mu)+p(\lambda)\to\rho(\nu)+p(\sigma)$ depend on x,Q^2,t

helicities





$$N_L = \tfrac{1}{2}\sum_{\lambda,\nu,\sigma}\left|T^{\nu\sigma}_{0\lambda}\right|^2 \qquad N_T = \tfrac{1}{2}\sum_{\lambda,\nu,\sigma}\left|T^{\nu\sigma}_{+\lambda}\right|^2$$

Standard analyses

- 23 SDMEs: bilinear, under-determined in the amplitudes
- L/T separation needs a separate multi-energy Rosenbluth analysis

This project

- Helicity amplitudes: magnitudes and relative phases
- σ_T and σ_L from the same inference; direct link to gluon GPDs

beam and target polarizations

All SFs(W_{XY}) depend on Q^2,x_B,t,ϕ,θ,φ

interference between longitudinal and transverse ρ

longitudinal rho

transverse rho

$$W_{XY}(\phi,\varphi,\vartheta) = \frac{3}{4\pi}\left[\cos^2\vartheta\, W^{LL}_{XY}(\phi) + \sqrt{2}\cos\vartheta\,\sin\vartheta\, W^{LT}_{XY}(\phi,\varphi) + \sin^2\vartheta\, W^{TT}_{XY}(\phi,\varphi)\right]$$

- Every event carries three decay angles (cosθ, φ, Φ), its kinematics (x_B, Q^2, W, t) and the beam energy
- Angles fix the shape, rates at several beam energies fix the L/T scale: **the information is in the data**

HEP: from HSF→Helicity amplitudes

$$\gamma^*(\mu) + p(\lambda) \to V(\nu) + p'(\sigma) \quad \rightarrow \quad \boxed{T^{\nu\sigma}_{\mu\lambda}(W, Q^2, t)}, \quad \mu, \nu \in \{-1, 0, +1\}, \quad \lambda, \sigma \in \{-\tfrac{1}{2}, +\tfrac{1}{2}\}$$

$$\mathcal{K}_{\rm hel} \equiv \frac{\alpha y(1-x)}{8\pi^3 x(1-\epsilon)}$$

$$\frac{\mathrm{d}\sigma^{\rm excl}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}t\,\mathrm{d}\phi_h} = \mathcal{K}_{\rm hel} \sum_{XY} \mathcal{W}_{XY}[\mathscr{F}]$$

Sivers type contributions for Transverse Target

$$\mathscr{F}^{\sin(\phi_h-\phi_S)}_{UT,T} = -\,\mathrm{Im}\,\mathcal{H}^{+-}_{++} = -\mathcal{C}\,\mathrm{Im}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{+-}\,(T^{\nu\sigma}_{++})^*,$$

$$\mathscr{F}_{UU,T} = \tfrac{1}{2}(\mathcal{H}^{++}_{++} + \mathcal{H}^{--}_{++}) = \frac{\mathcal{C}}{2}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{++}|^2 + |T^{\nu\sigma}_{+-}|^2\right)$$

$$\epsilon\ \mathscr{F}^{\sin(\phi_h-\phi_S)}_{UT,L} = -\,\mathrm{Im}\,\mathcal{H}^{+-}_{00} = -\mathcal{C}\,\mathrm{Im}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{0+})^*,$$

$$\mathscr{F}_{UU,L} = \mathcal{H}^{++}_{00} = \mathcal{C}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} |T^{\nu\sigma}_{0+}|^2,$$

$$\sqrt{2\epsilon(1+\epsilon)}\ \mathscr{F}^{\sin\phi_S}_{UT} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}\,\mathcal{H}^{+-}_{+0} = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{++})^*$$

$$\mathscr{F}^{\cos\phi_h}_{UU} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathcal{H}^{++}_{+0} + \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Re}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} \left[T^{\nu\sigma}_{0+}\,(T^{\nu\sigma}_{++})^* + T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{+-})^*\right]$$

$$\mathscr{F}^{\cos\phi_h}_{LL} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathcal{H}^{++}_{+0} - \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Re}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} \left[T^{\nu\sigma}_{0+}\,(T^{\nu\sigma}_{++})^* - T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{+-})^*\right]$$

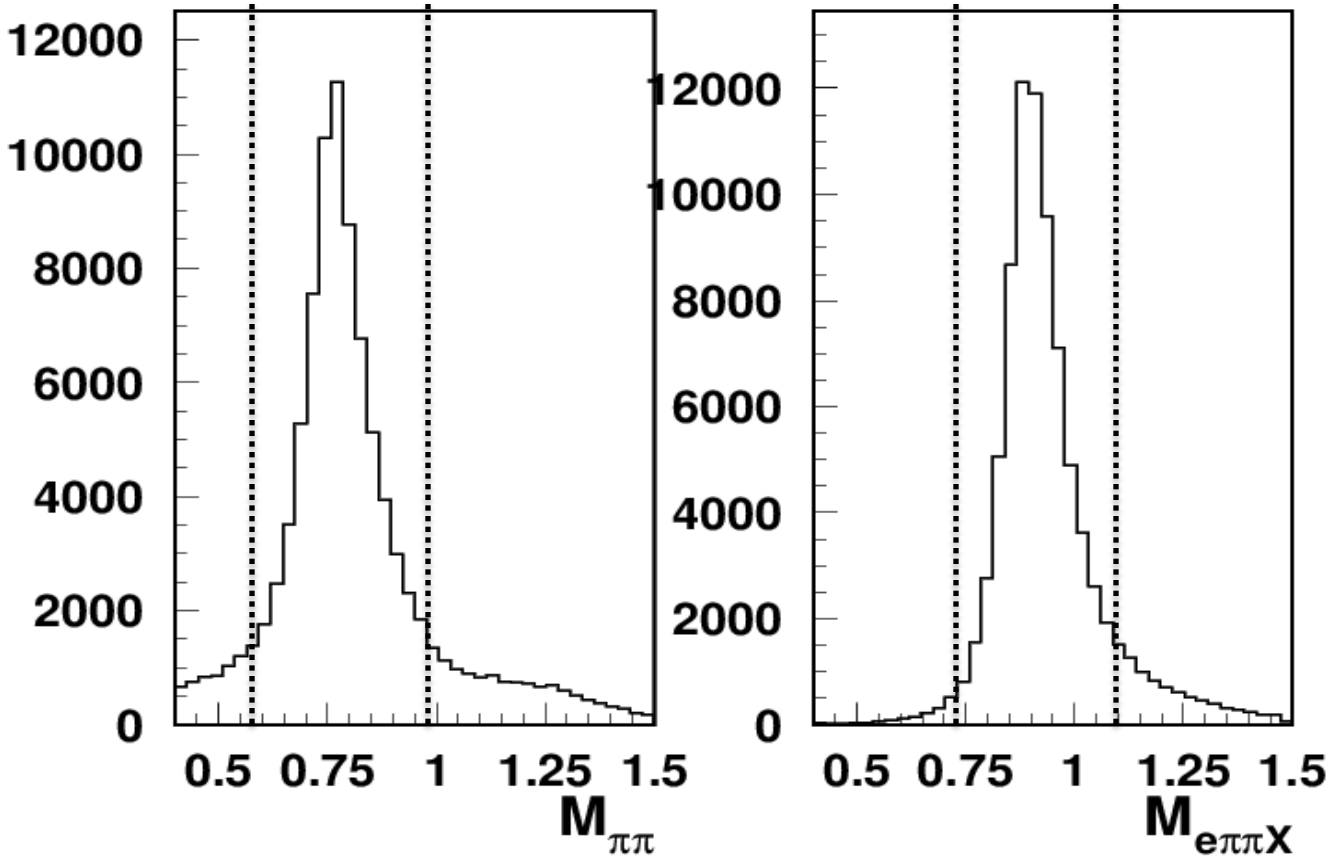
$$\sqrt{2\epsilon(1-\epsilon)}\ \mathscr{F}^{\sin\phi_h}_{LU} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+0} + \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} \left[T^{\nu\sigma}_{0+}\,(T^{\nu\sigma}_{++})^* + T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{+-})^*\right]$$

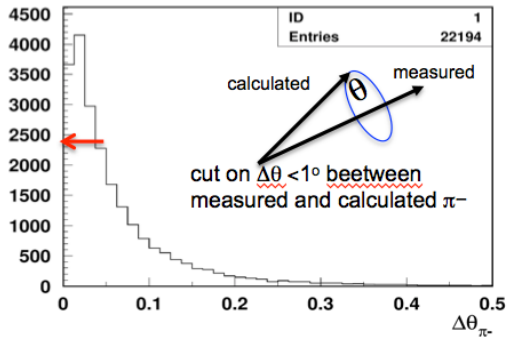
$$\mathscr{F}^{\sin\phi_h}_{UL} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+0} - \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}} \left[T^{\nu\sigma}_{0+}\,(T^{\nu\sigma}_{++})^* - T^{\nu\sigma}_{0-}\,(T^{\nu\sigma}_{+-})^*\right]$$

- Interconnection of observables more relevant in exclusive limit, where they connect directly to same helicity amplitudes
- Observables with transverse target provide independent access to proton helicity flip amplitudes

Backgrounds: CLAS12 RGA 10.6 GeV

Background to exclusive rho mainly includes other exclusive 2 pion samples with non exclusive rhos (<5-10%, to be finalized with proper account of BW tails)
Detection of all 4 final state particles allows introduction of strict cuts (Q^2>1,W>2)

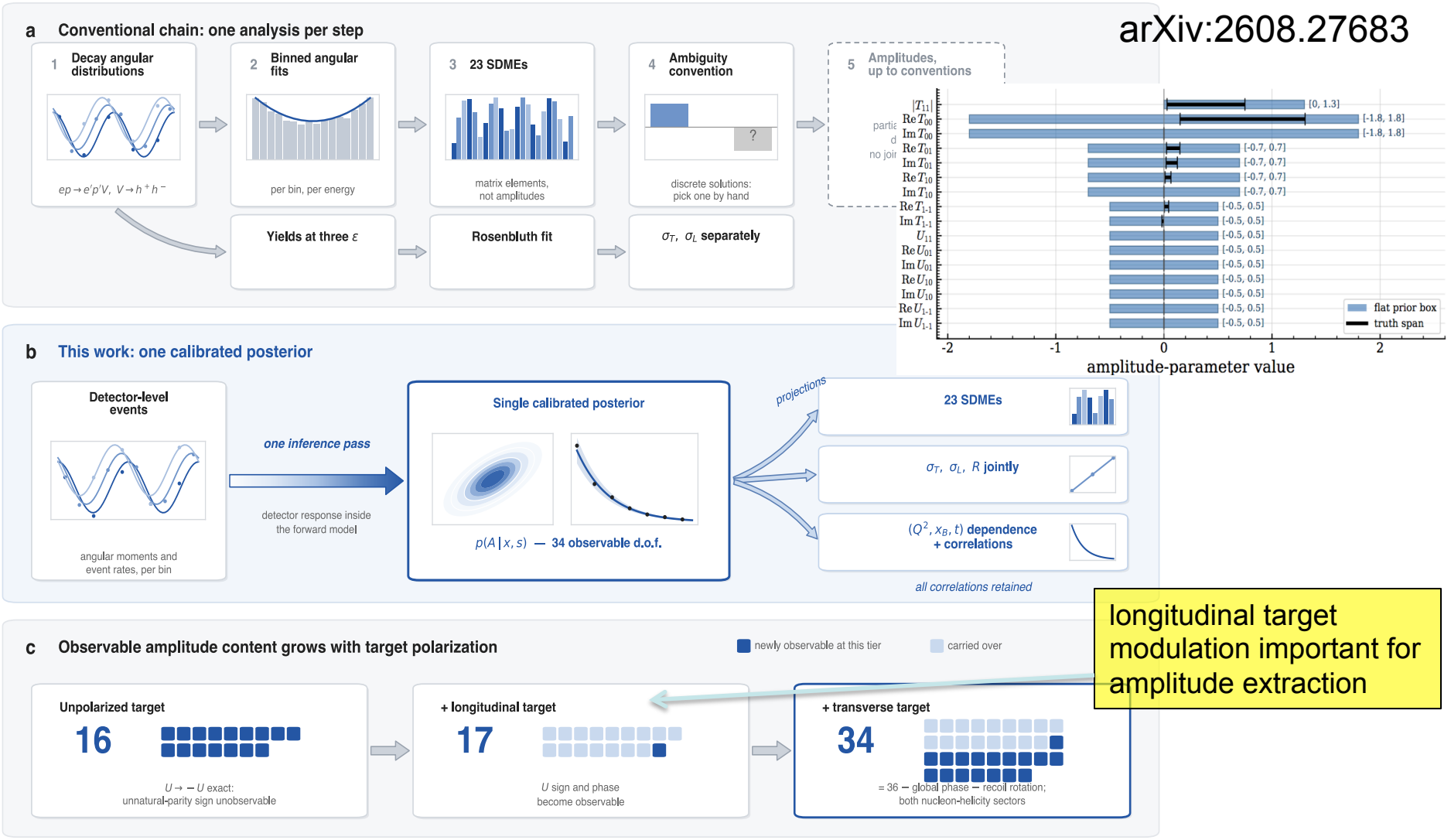




Contributions from other 2pi exclusive states could be evaluated using dedicated MC

Direct Bayesian Inference of Helicity Amplitudes from Detector-Level Data

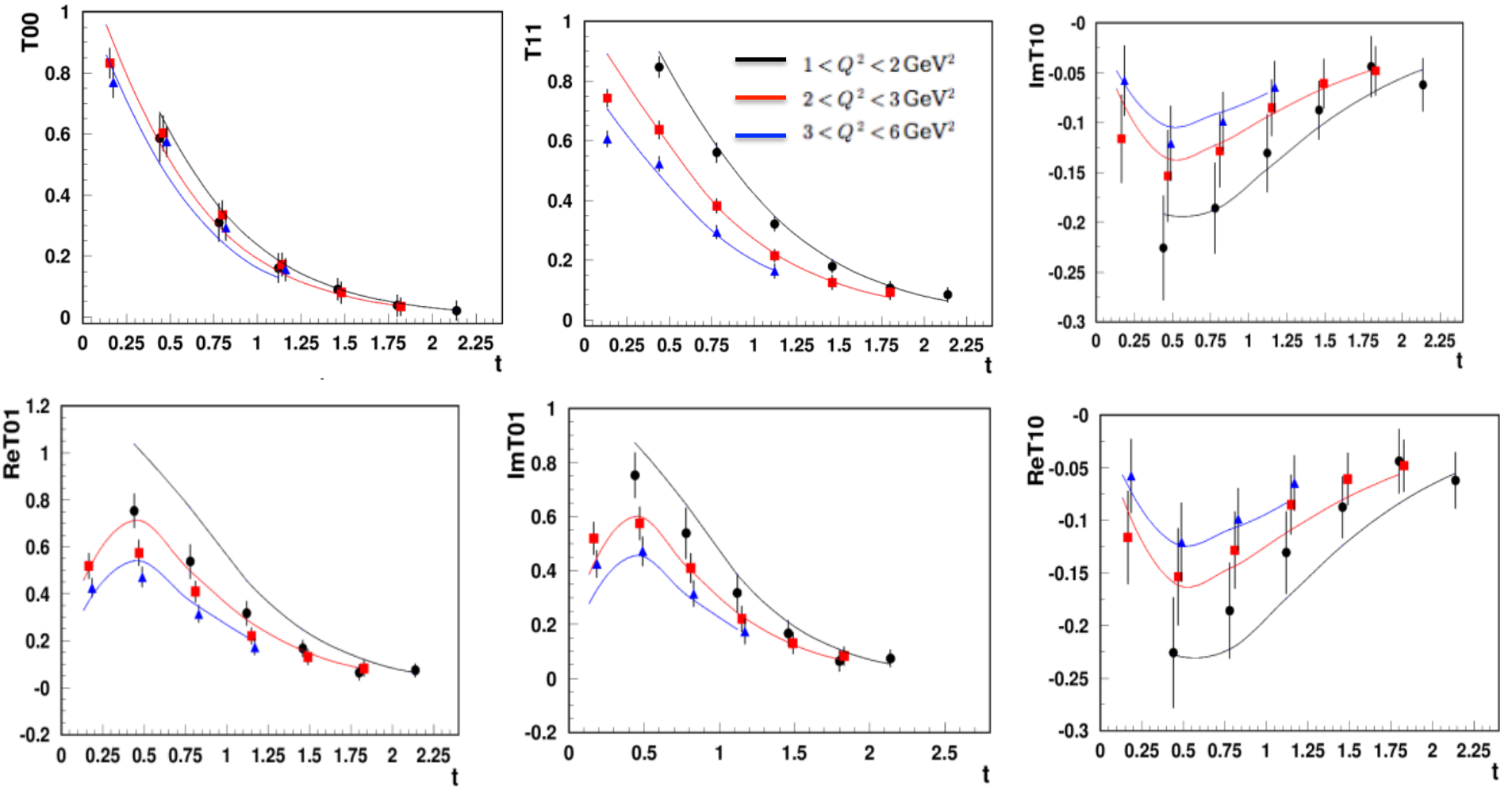
arXiv:2608.27683



longitudinal target modulation important for amplitude extraction

set of amplitudes (A) set of conditions with min/max of amplitudes (s)

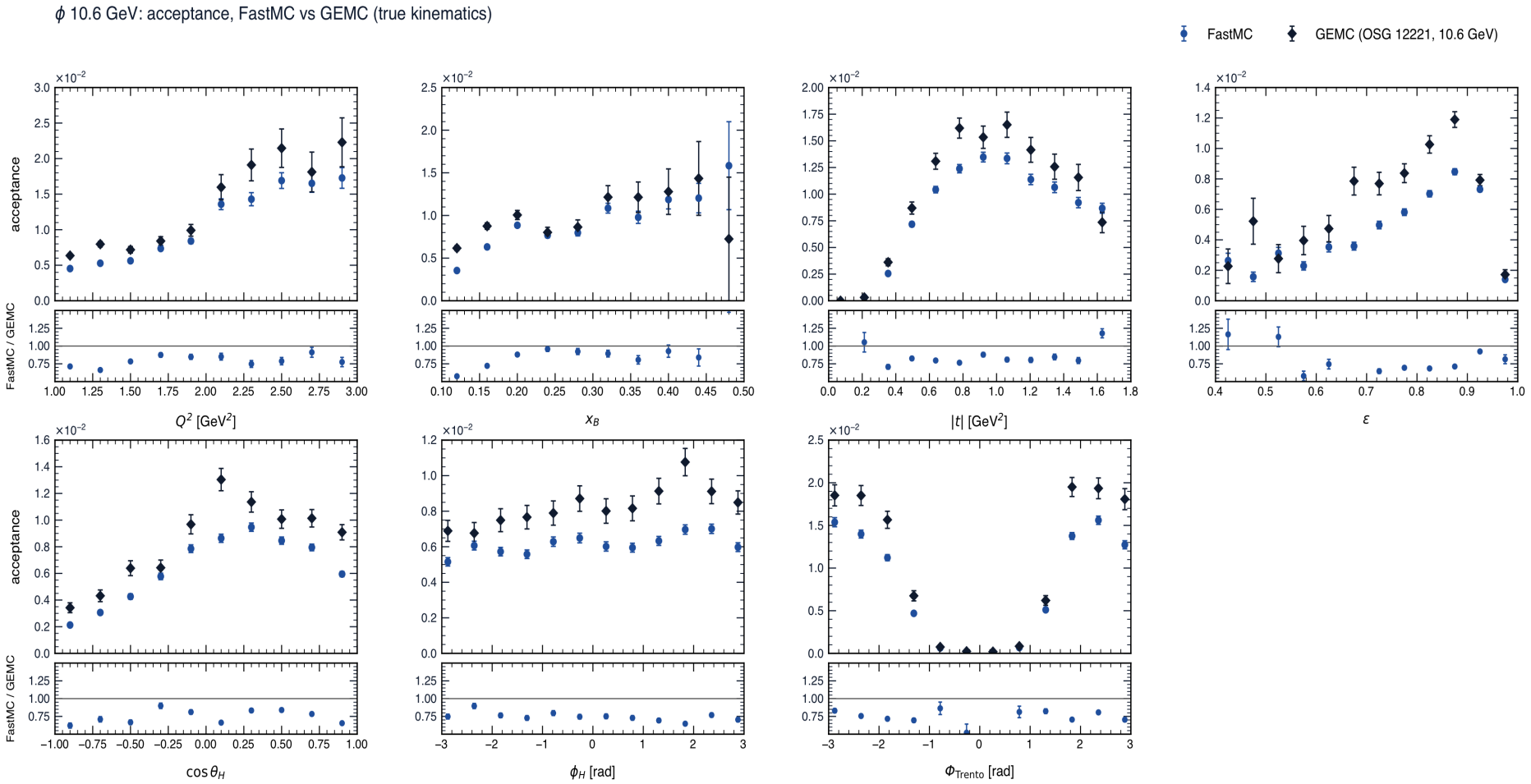
Validating the Direct Bayesian Inference framework



the framework is able to recover the amplitude (curves→generated) , most importantly with controlled systematics!!!

Acceptance effects 7dim variables

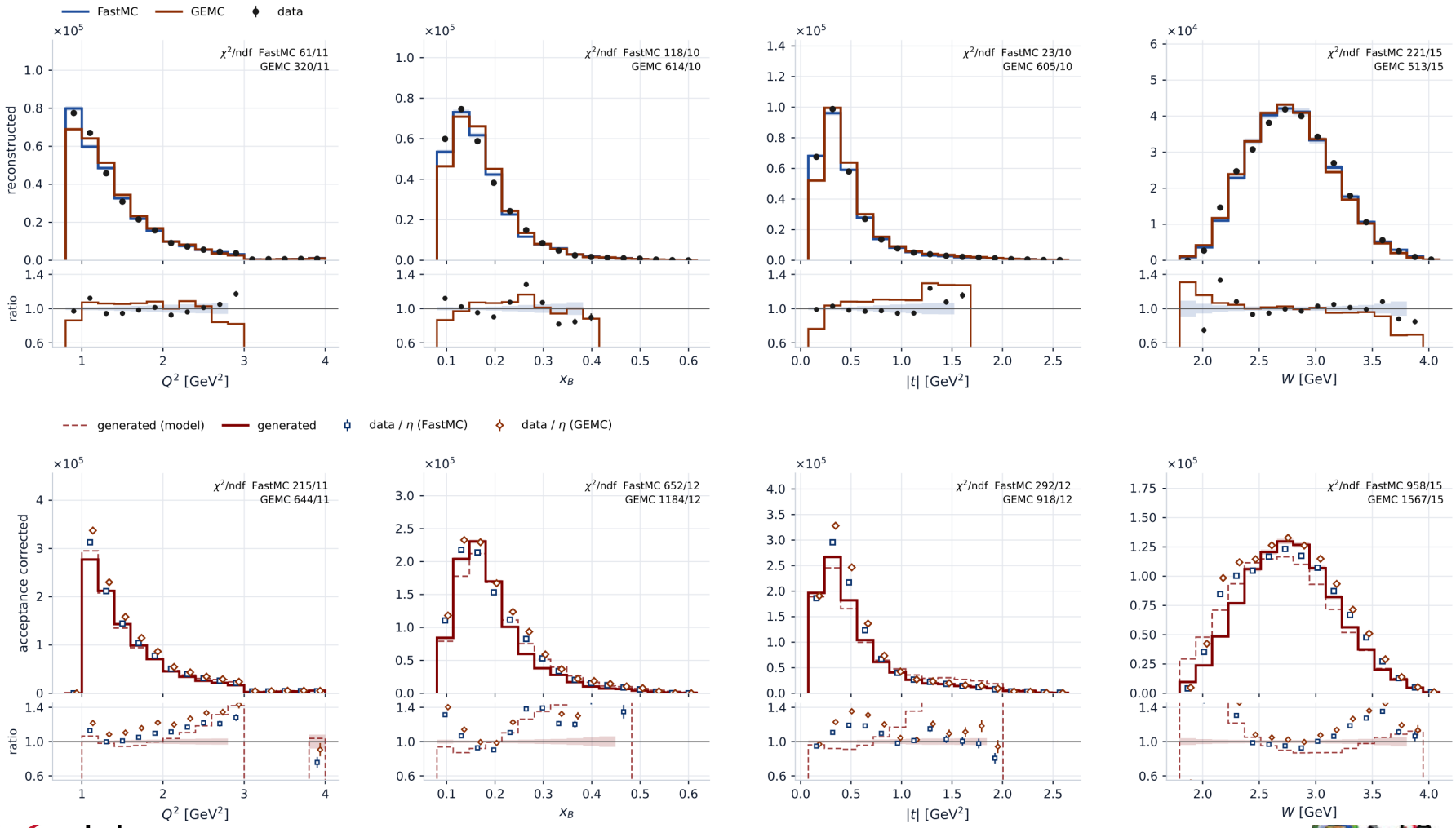
- 10.6 Fall 2018 outbending



7D acceptance very sensitive to generation and reconstruction details!!!

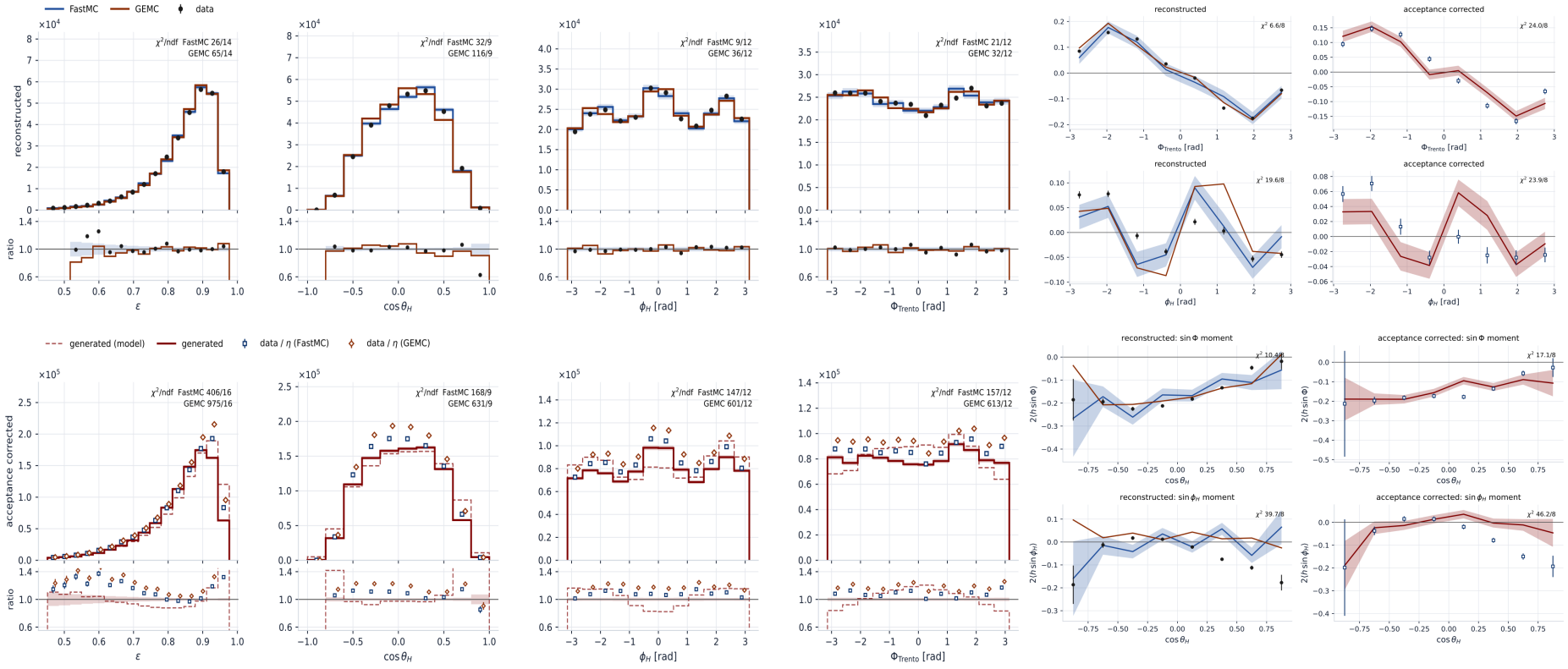
Comparing simulations with data for exclusive ρ

- Plug in the amplitudes and compare simulations (FastMC) and GEMC to emulated acceptance and resolutions and tracking efficiency of the detector with data (subtracted background)



Comparing simulations with data for exclusive ρ

- Plug in the amplitudes and compare simulations (FastMC) and GEMC to emulated acceptance and resolutions and tracking efficiency of the detector with data (subtracted background)

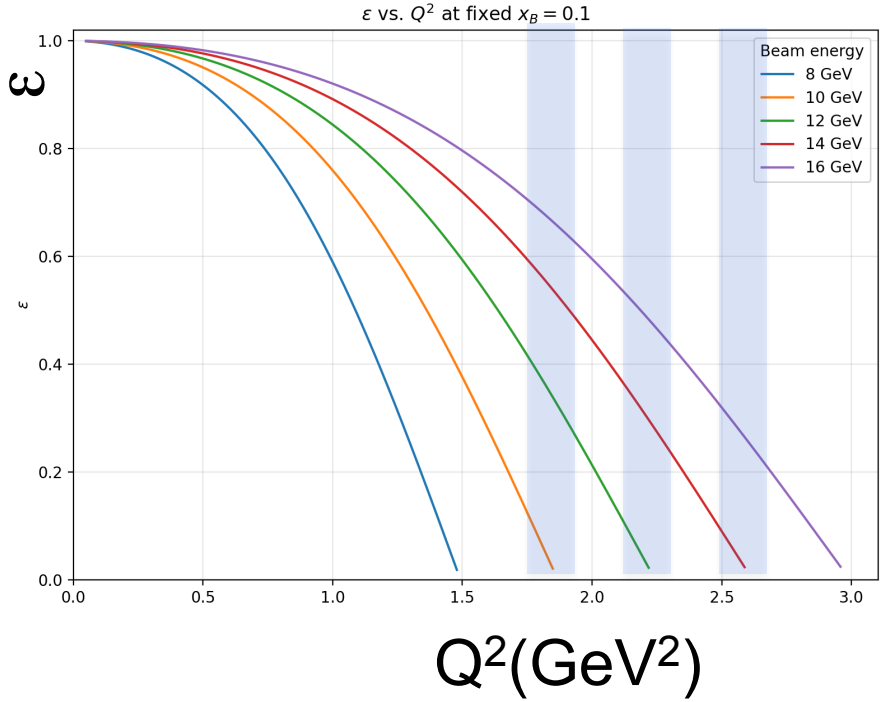


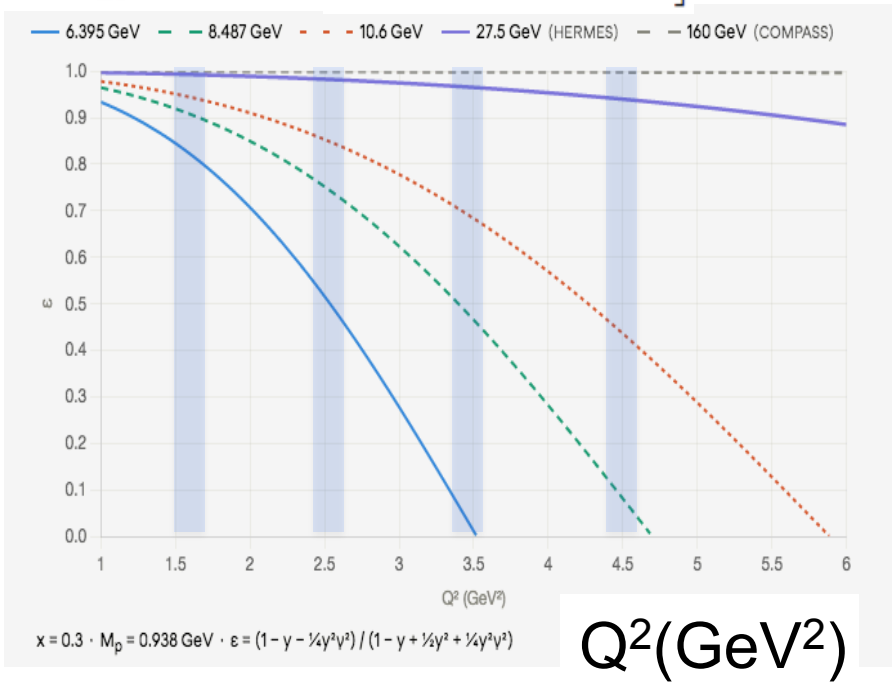
Reasonable agreement for most observables, acceptances for 1st iteration still different

ε-dependence for electroproduction experiments

CLAS12 already collected data on proton for 6.4,6.5,7.5.8.5.10.2,10.6 GeV

$$\frac{d^4\sigma}{dx_B\,dQ^2\,dt\,d\phi} = \frac{\Gamma_H}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + P_\ell\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin\phi\right]$$





Combining measurements (will benefit from "event base" framework) at different energies of JLab and HERMES/COMPASS will be important for model independent separation of dynamical contributions in a wide Q^2 range with controlled systematics

Wider range in Q^2 (making bridge with COMPASS/EIC) will benefit from energy upgrade

From HSFs to Helicity Amplitudes

$T^{\nu\sigma}_{\mu\lambda}$ helicity amplitudes describing $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$ depend on x,Q^2,t

helicities

$$\mu, \nu \in \{-1, 0, +1\}, \quad \lambda, \sigma \in \{-\tfrac{1}{2}, +\tfrac{1}{2}\}.$$

$$F_{UU,T} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} + \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 + |T^{\nu\sigma}_{+1,-}|^2\right)$$

$$F_{UU,L} = \mathcal{H}^{++}_{0,0} = \mathcal{C} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} |T^{\nu\sigma}_{0,+}|^2$$

$$F_{LL} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 - |T^{\nu\sigma}_{+1,-}|^2\right)$$

↓ pion limit v=0

$$\frac{d\sigma_{LL}}{dt} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{0\sigma}_{+1,+}|^2 - |T^{0\sigma}_{+1,-}|^2\right)$$

$$P_T^2(t) \simeq -(1 - x_B)t = (1 - x_B)|t|$$

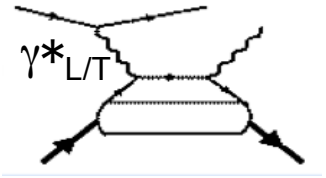
amplitude	photon	nucleon	Δ	forward factor K
$M_{0+,0+}$	L	non-flip	0	1
$M_{0-,0+}$	L	flip	−1	$\sqrt{-t'}/2M_p$
$M_{0+,++}$	T(+1)	non-flip	+1	$\sqrt{-t'}/2M_p$
$M_{0-,++}$	T(+1)	flip	0	1
$M_{0+,-+}$	T(−1)	non-flip	−1	$\sqrt{-t'}/2M_p$
$M_{0-,-+}$	T(−1)	flip	−2	$-t'/4M_p^2$

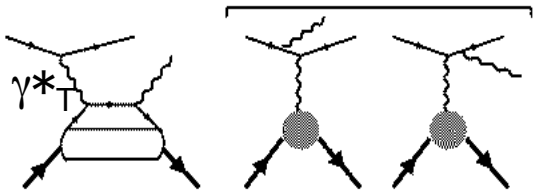
π^0 γ^*_T

six independent amplitudes

Cross sections of exclusive processes extracted in terms of helicity SFs provide direct/complementary access to underlying amplitudes

Helicity amplitudes: DVCS





$\sin\phi$ in pure DVCS squared $\longleftrightarrow$ twist-2 $\times$ twist-3,

$\sin\phi$ in BH–DVCS $\longleftrightarrow$ BH $\times$ twist-2 DVCS.

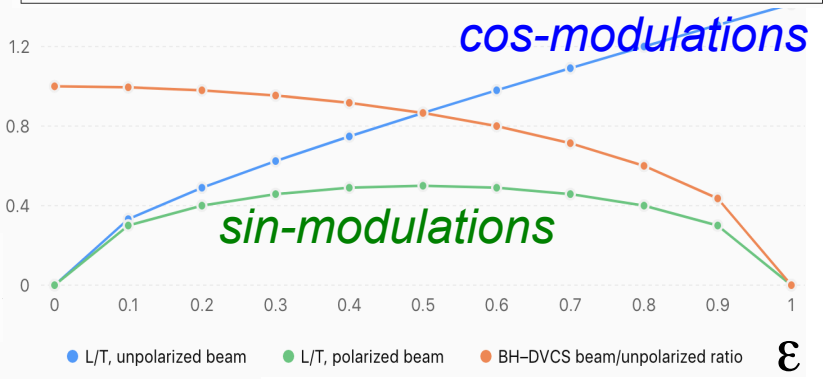
$$U_{0+} = \frac{1}{2\mathcal{D}} \sum_{\nu=\pm1} \sum_{\sigma,\lambda} T^{\nu\sigma}_{0\lambda} \left(T^{\nu\sigma}_{+1,\lambda}\right)^*$$

$$W^{\rm DVCS}_{LU} = -2\sqrt{\epsilon(1-\epsilon)}\,{\rm Im}\,U_{0+}\sin\phi$$

DVCS L/T : $\quad {\rm Im}(T_L T_T^*)$,

BH $-$ DVCS : $\quad {\rm Im}(T_{\rm BH} T_T^*)$

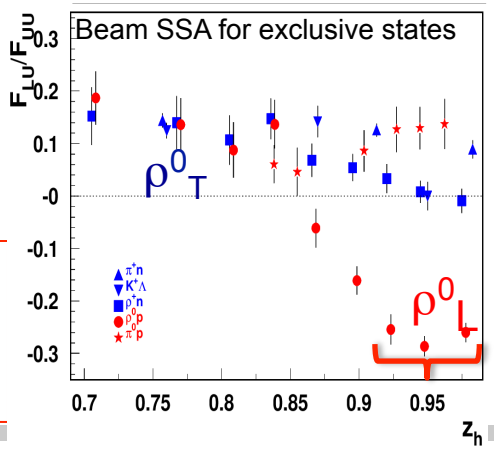
$$s^{\mathcal{I}}_{1,\rm unp} = 16K(\epsilon)P_\ell \frac{\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\,{\rm Im}\,\mathcal{C}^{\mathcal{I}}_{\rm unp}$$



Observable	Pure DVCS: L/T interference	BH–DVCS interference: leading harmonic
UU	$\cos\phi\ {\rm Re}(T_0 T_+^*)$	$\cos\phi\ {\rm Re}\,\mathcal{C}^{\mathcal{I}}_{UU}$
LU	$\sin\phi\ {\rm Im}(T_0 T_+^*)$	$\sin\phi\ {\rm Im}\,\mathcal{C}^{\mathcal{I}}_{UU}$
UL	$\sin\phi\ {\rm Im}(T_0 T_+^*)$, helicity difference	$\sin\phi\ {\rm Im}\,\mathcal{C}^{\mathcal{I}}_{LP}$
LL	$\cos\phi\ {\rm Re}(T_0 T_+^*)$, helicity difference	$\cos\phi\ {\rm Re}\,\mathcal{C}^{\mathcal{I}}_{LP}$
UT	$\sin(\phi-\phi_S)\cos\phi$ and $\cos(\phi-\phi_S)\sin\phi$	Transverse-target spin harmonics involving ϕ, ϕ_S
LT	$\sin(\phi-\phi_S)\sin\phi$ and $\cos(\phi-\phi_S)\cos\phi$	Corresponding beam–transverse-target spin harmonics

$$R_{LT/\mathcal{I}} = \frac{x_B y(-t)|\mathcal{P}_1\mathcal{P}_2|}{Q^2(2-x_B)(2-y)} \left|\frac{{\rm Im}\,\mathcal{C}^{\rm DVCS}_{\rm unp}(\mathcal{F}^{\rm eff},\mathcal{F}^*)}{{\rm Im}\,\mathcal{C}^{\mathcal{I}}_{\rm unp}(\mathcal{F})}\right|$$

$$R(t) \sim \frac{|t|\,|\mathcal{P}_1\mathcal{P}_2|}{|F_1(t)|} e^{B_3 t/2} \qquad \mathcal{H}^{\rm eff}(t) \sim e^{B_3 t/2}$$

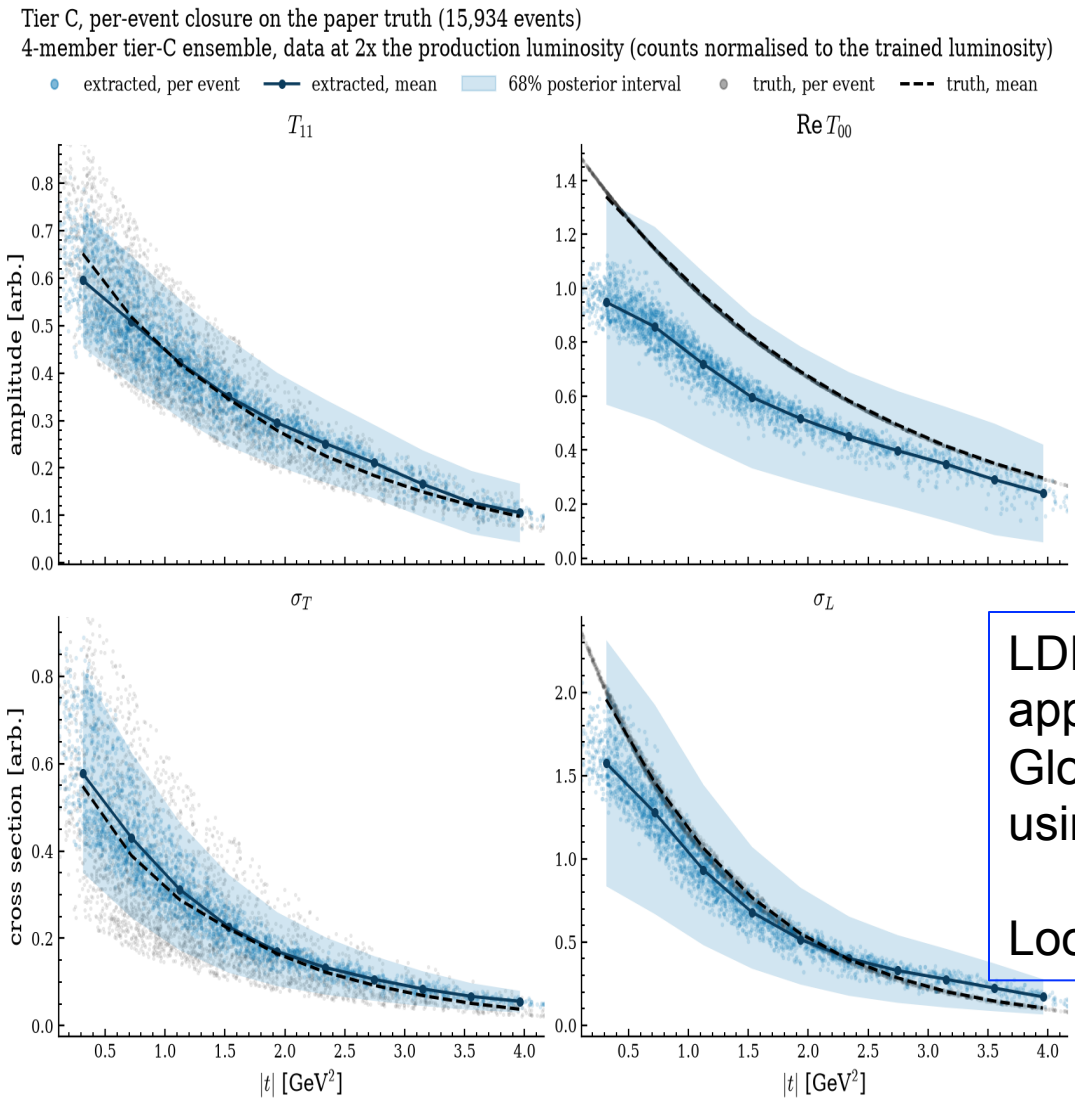


-For all exclusive final states dominated by u-quarks Beam SSA~10-15%

-DVCS L/T vs BH-DVCS interference contributions have different ε t, and Q^2-dependences and can be separated in precision measurements

feasibility study for event-by-event closure

infer the physics of vector meson production in the exclusive electroproduction reaction in electron proton scattering experiment!



- **15,934 events**, each with a posterior at its own (Q^2, x_B, t)
- T_{11}, σ_T and σ_L track the injected truth over $0.3 < |t| < 4$ GeV^2
- Truth inside the 68% band at **39 of 40** binned points

Full polarized target (tier C), 4-member ensemble, simulated data at 2× the production luminosity

LDRD proposal (B. Singh Co-PI) approved for 2 years
Global Extraction of Helicity Amplitudes using Event-by-Event framework

Looking for an interested post-doc

Combining run groups: using process files

YAML-header

```
# format_version: 1.0
# experiment: CLAS12
# beam_energy: 10.55
# columns:
#   - {name: run, unit: "1", description: "run number"}
#   - {name: event, unit: "1", description: "event number"}
#   - {name: hel-lep, unit: "1", description: "lepton helicity"}
#   - {name: hel-lpro, unit: "1", description: "proton helicity"}
#   - {name: el_e, unit: "GeV", description: "e- energy"}
#   - {name: el_t, unit: "rad", description: "e- polar angle"}
#   - {name: el_f, unit: "rad", description: "e- azimuthal angle"}
#   - {name: el_z, unit: "cm", description: "e- z-vertex"}
#   - {name: pp_e, unit: "GeV", description: "pi+ energy"}
#   - {name: pp_t, unit: "rad", description: "pi+ polar angle"}
#   - {name: pp_f, unit: "rad", description: "pi+ azimuthal angle"}
#   - {name: pp_z, unit: "cm", description:  "pi+ z-vertex"}
#   - {name: pm_e, unit: "GeV", description:  "pi- energy"}
#   - {name: pm_t, unit: "rad", description: "pi- polar angle"}
#   - {name: pm_f, unit: "rad", description: "pi- azimuthal angle"}
#   - {name: pm_z, unit: "cm", description: "pi- z-vertex"}
#   - {name: pr_e, unit: "GeV", description: "proton energy"}
#   - {name: pr_t, unit: "rad", description: "proton polar angle"}
#   - {name: pr_f, unit: "rad", description: "proton azimuthal angle"}
#   - {name: pr_z, unit: "cm", description: "proton z-vertex"}
#   - {name: pimang, unit: "rad", description: "cone angle for pi-"}
#   - {name: phi, unit: "rad", description: "phi-trento"}
#   - {name: cost, unit: "rad", description: "original supplied angular field, not a cosine; definition unverified"}
#   - {name: varphi, unit: "rad", description: "varphi"}
#   - {name: W_calc, unit: "GeV", description: "invariant mass W from initial proton and scattered-electron four-momentum"}
#   - {name: Phi_Diehl, unit: "rad", description: "Trento lepton-to-dipion production-plane angle"}
#   - {name: varphi_Diehl, unit: "rad", description: "pi+ azimuth in dipion rest frame, z=-recoil p and x=target transverse"}
#   - {name: theta_Diehl, unit: "rad", description: "pi+ polar angle in dipion rest frame relative to -recoil p; range [0,pi]"}
#
# reaction: "e p -> e_prime p_prime pi_plus pi_minus"
# beam_axis: "+z laboratory"
# target: "stationary proton"
# reconstructed_meson: "pi+ + pi-"
# angle_convention: "Diehl arXiv:0704.1565v2 section 2, Figures 1-2"
# angle_range: "Phi_Diehl and varphi_Diehl in [0,2pi); theta_Diehl in [0,pi]"
# beam_energy_source: "command-line --beam-energy (default 10.55 GeV); never sum of final-state energies"
# note: "Existing phi,cost,varphi preserved; they are not assumed identical to reconstructed Diehl angles"
# DATA:
   16982     38786  1  1   6.648   0.176   5.198  -1.315   0.523   0.821   2.582  -3.471   3.199   0.268   2.197  -0.990   1.162   0.424   0.436
   16982     73600 -1  1   7.427   0.185   3.280  -3.516   1.305   0.375   5.631  -5.594   1.387   0.576   0.534  -4.071   1.267   0.389   0.236
   16982     83938 -1  1   6.380   0.192   0.339  -4.162   2.307   0.174   2.667  -8.435   1.579   0.339   4.197  -3.765   1.186   0.821   3.401
   16982    137255  1  1   5.542   0.184   2.303  -2.222   1.815   0.368   6.045  -3.155   2.113   0.574   5.256  -2.297   1.977   0.404   2.541
   16982    411965 -1  1   7.005   0.167   4.148  -3.275   0.901   0.368   2.284  -3.608   2.262   0.350   0.376  -2.745   1.192   0.669   1.315
   16982    418143 -1  1   6.949   0.144   4.262  -3.848   0.972   0.304   0.139  -5.947   2.245   0.531   1.149  -3.910   1.264   0.421   3.720
   16982    450572 -1  1   6.475   0.200   5.505  -2.524   2.476   0.324   2.610  -4.489   1.235   0.575   1.909  -3.483   1.190   0.220   4.634
   16982    519869 -1  1   1.552   0.533   2.580  -2.695   0.695   0.378   5.450  -5.615   7.618   0.144   5.231  -2.053   1.436   0.617   1.525
   16982    548562 -1  1   2.683   0.343   2.340  -2.808   2.048   0.297   6.230  -4.213   5.397   0.142   5.438  -1.925   1.082   1.188   3.448
   16982    650277 -1  1   6.508   0.207   1.975  -4.215   0.626   0.794   4.805  -4.207   2.892   0.334   5.576  -3.929   1.162   0.495   3.640
   16982    669259 -1  1   4.228   0.331   2.555  -0.085   1.850   0.292   6.111  -1.547   4.177   0.207   5.384   0.115   1.172   0.260   0.189
   16982    743767 -1  1   3.916   0.258   3.094  -0.461   3.875   0.170   0.561  -5.025   2.473   0.347   6.089  -1.742   1.170   0.631   3.649
   16982    852771  1  1   6.079   0.214   2.144  -0.269   1.283   0.597   5.065  -1.968   2.535   0.334   5.105  -0.784   1.317   0.430   1.360
```

Files directly readable by AI, without any further explanation of content

Will need for signal, background, MC including, generated and reconstructed, where available.

Experimental extraction in SI era

- Separating L/T photon contributions critical for interpretation of Hard Exclusive Processes, also important for SIDIS
- Move from cross sections and multiplicities to spin dependent multiplicities/ cross sections (helicity SFs)
- Detailed understanding of multi-dimensional acceptances critical for proper extraction of cross sections, in particular for longitudinal photon contributions dominated by longitudinal VMs
- Develop a framework for exclusive processes based on helicity amplitudes and extraction frameworks based on helicity amplitudes, combining data sets with polarized and unpolarized targets
- Development of a realistic MCs for exclusive processes based on helicity amplitudes (currently available for ρ, $\pi 0$ $\pi+$) for validation of complex extraction frameworks becomes high priority

Plans for future

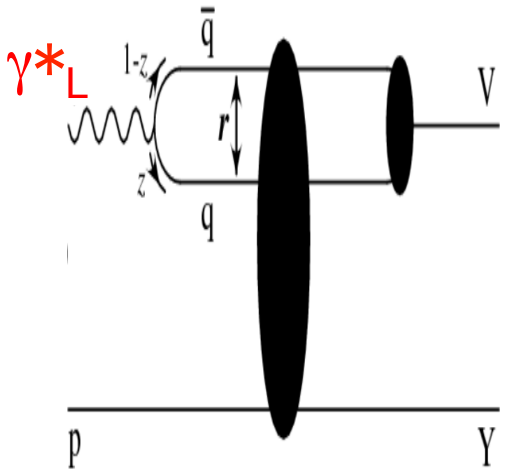
- Combine RGK/RGA/RGC for separating L/T photon contributions in Hard Exclusive processes, using extracted amplitudes
- Moving from bin-based analysis to event-based analysis will be important for extraction of helicity amplitudes from all targets, using process files for all relevant processes, including unpolarized and polarized hydrogen and deuteron
- Iteratively update the MC, using the complex extraction framework allowing realistic evaluation of required sizes of needed data sets, including RGH and lower/higher energy polarized RGC/RGN
- Push theory for development of the framework to include higher twist effects in Hard Exclusive processes, HT GPDs, GTMDs in particular (validation in Q^2-dependences of all relevant observables will be critical)

- support slides

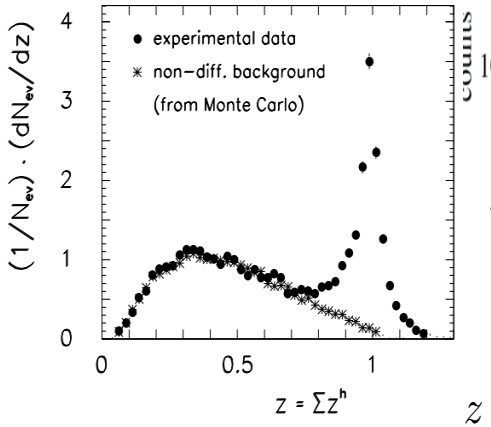
Exclusive VMs (ρ^0, ω,ϕ, J/Ψ,…)

$$\gamma^*(\mu) + p(\lambda) \rightarrow \rho(\nu) + p(\sigma)$$

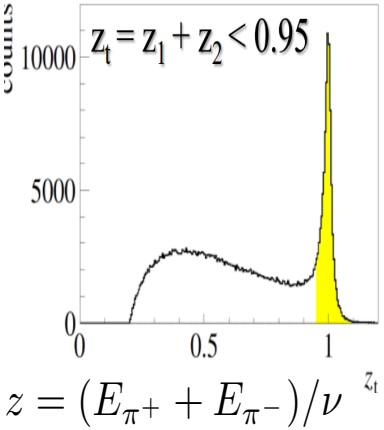
$\mu, \nu, \lambda, \sigma$ → helicities



E665 Eμ = 470 GeV

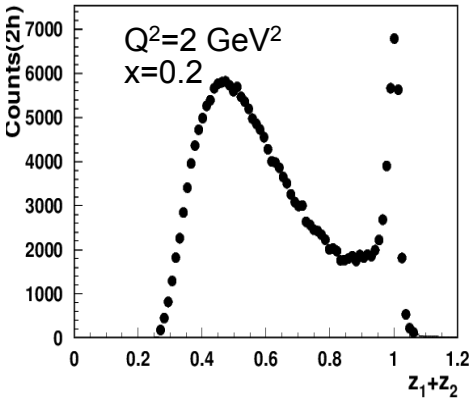


COMPASS Eμ = 160 GeV



$z = (E_{\pi^+} + E_{\pi^-})/\nu$

CLAS12 E=10.6 GeB



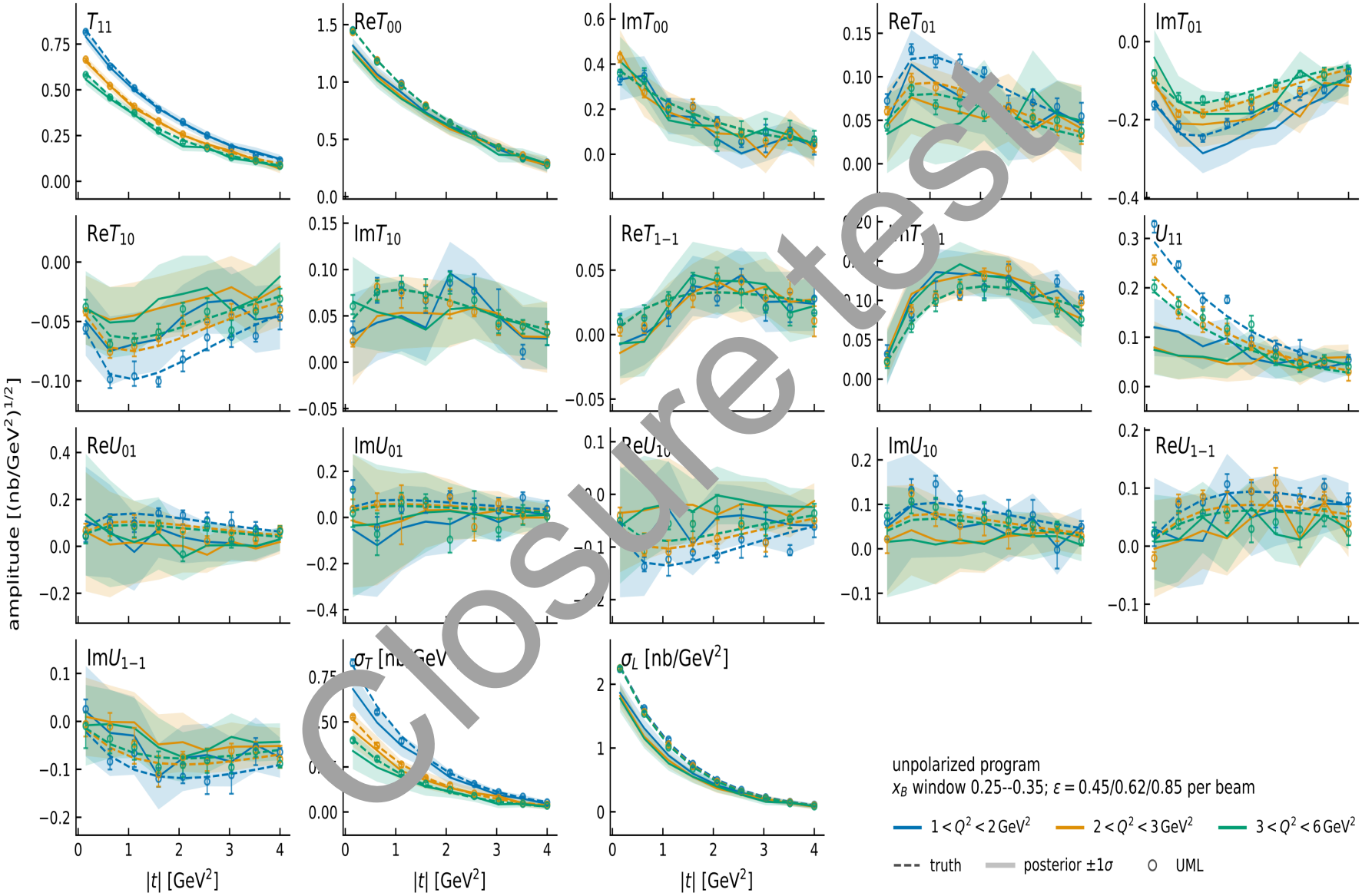
Estimated ~20% contributions from rho to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS

→most longitudinally polarized ρ^0

For GPD based interpretation need experimental separation of contributions

Studies of exclusive processes require high resolution and multidimensional measurements !!!
No indication of “Different rho at JLab”?

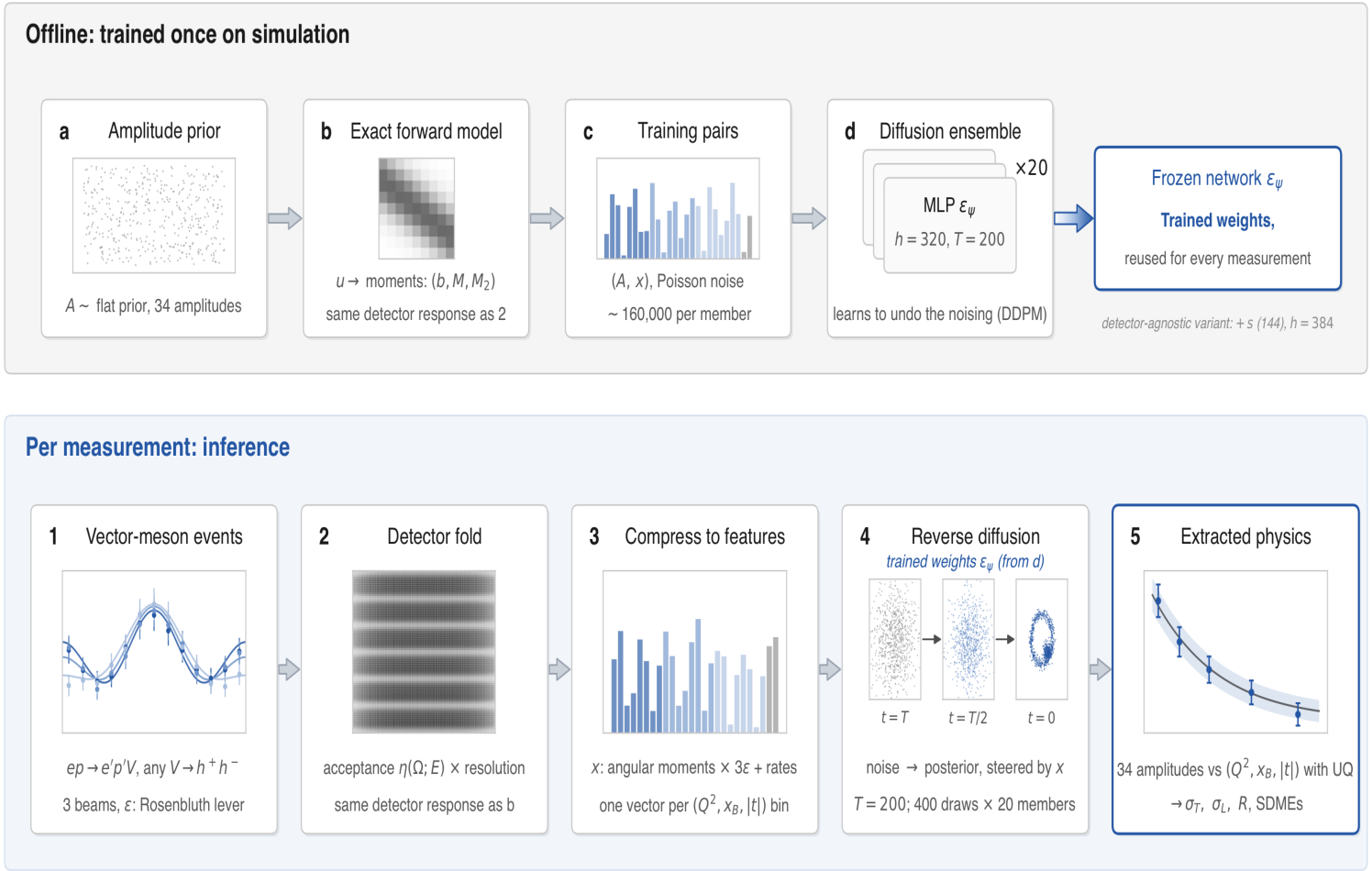
ϕ meson production on unpolarized



Closure test

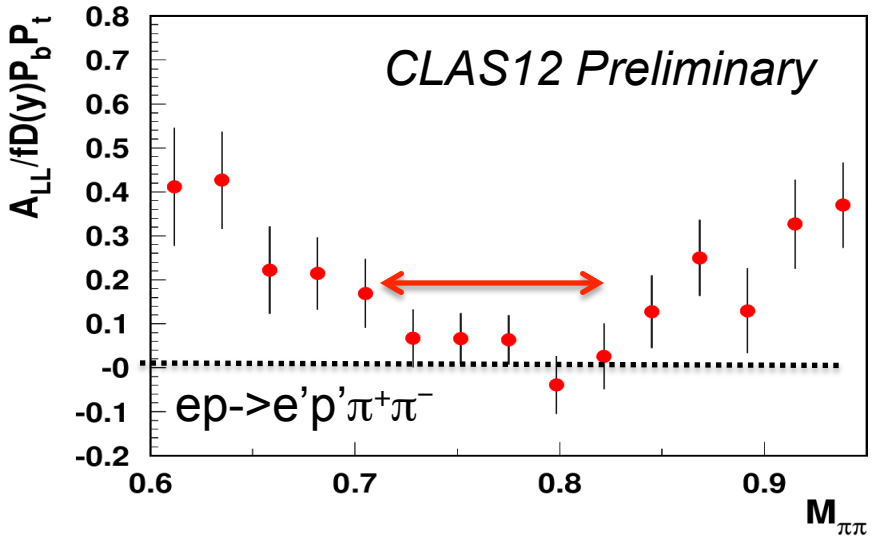
Work flow for extraction

- **A conditional diffusion model:** $q_\psi(u \mid x)$ — the third neural route, twin of the normalizing-flow NPE.
- Different engine: iterative denoising instead of one invertible map (flexible, correlated posteriors).



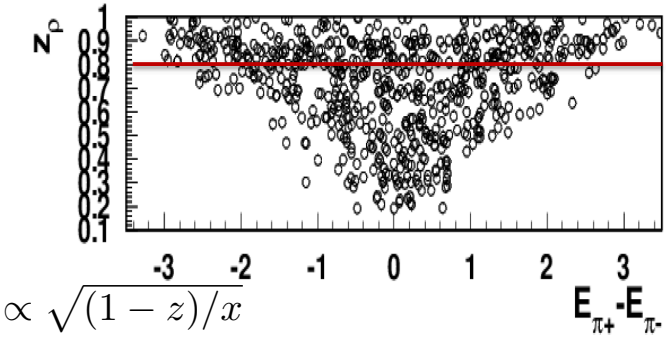
B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

Studies of ρ^0 impact with longitudinally polarized NH_3 target

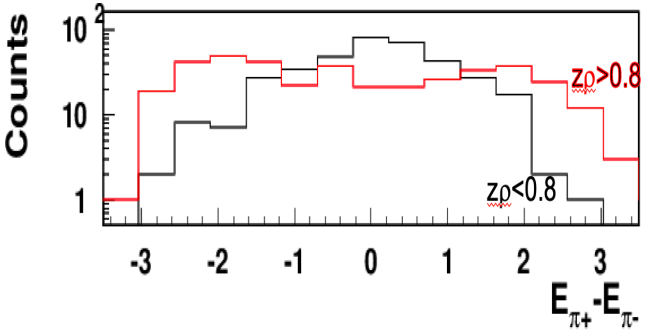


Need clear separation of hydrogen from NH_3
and "diffractive" exclusive ρ0s from exclusive $\pi+\pi-$

Polarization of rho



$$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$$



- DSA is P-even, SSA is P-odd
- longitudinal photon cross section is P-odd

→ contribution appears only in the SSA, a P-odd observable, and does not appear in DSA(→significant dilution in DSA)

At large z (small t) the shapes of distributions (getting asymmetric) clearly indicate dominance of longitudinal rho

Modifying the phenomenology

Use the same formalism for Master Formula for eN → e′hX , for direct extraction of helicity structure functions (HSFs) from data, both for SIDIS and exclusive limit. In exclusive case express cross sections directly in terms of helicity amplitudes, both in extraction framework and MC for validation of results.

Develop a realistic MC using the helicity amplitudes with physics motivated kinematical dependences with subsequent calculations of Helicity Structure Functions, SDMEs and regular SFs
→Realistic SIDIS MC needed for proper evaluation of exclusive backgrounds
→Realistic exclusive MC (VMs, in particular) needed for evaluation of SIDIS backgrounds

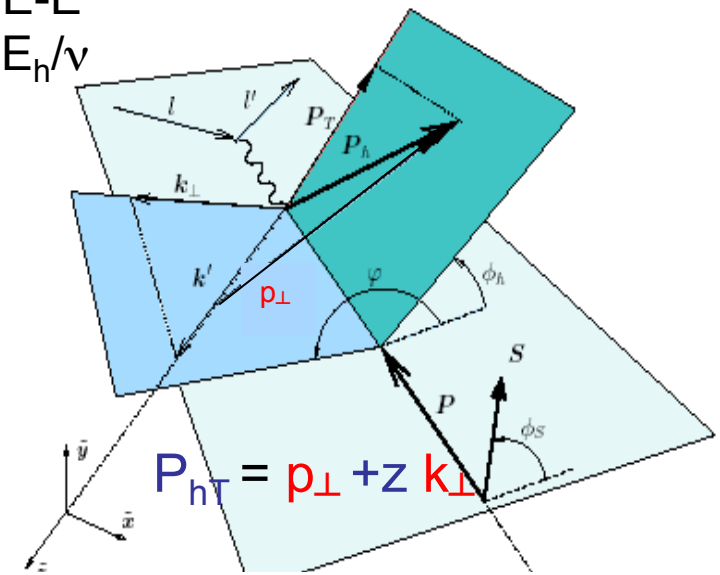
Add proper description of exclusive rhos and pions in the polarized PYTHIA, with the latest fragmentation functions from Belle to evaluate the σ_T in the exclusive limit, compare with BKM

Run the full generation, reconstruction, and amplitude extraction chain for different beam energies at JLab and COMPASS, check the L/T ratio extraction with direct Rosenbluth separation, combining JLab and COMPASS data

Push for development of the factorization based description of exclusive processes including the higher twist GPDs

DIS kinematical coverage and observables

ν=E-E'
$z=E_h/\nu$



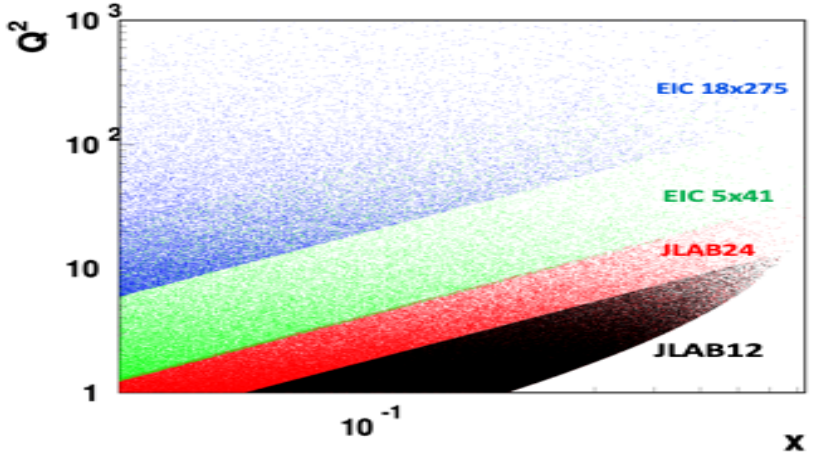


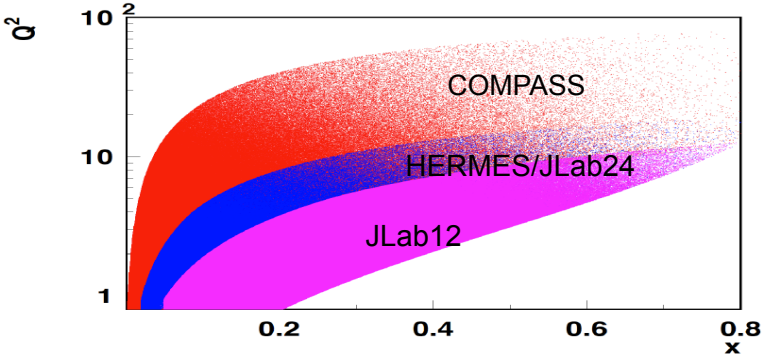


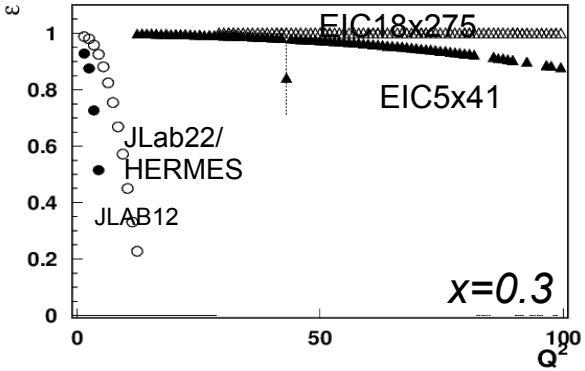




$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

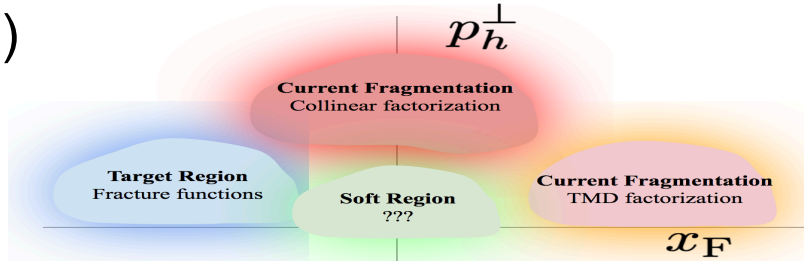


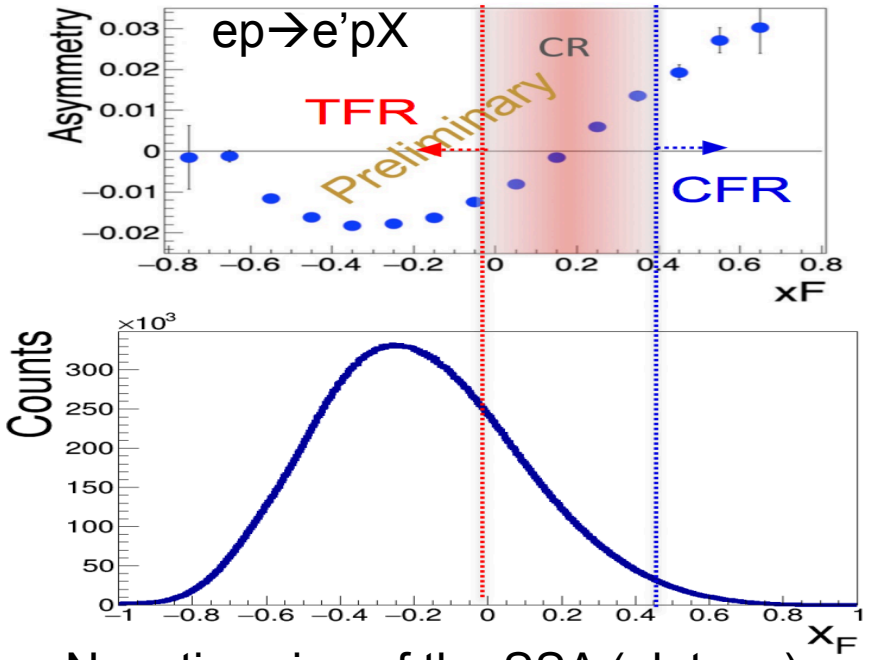




Measuring target fragmentation at JLab

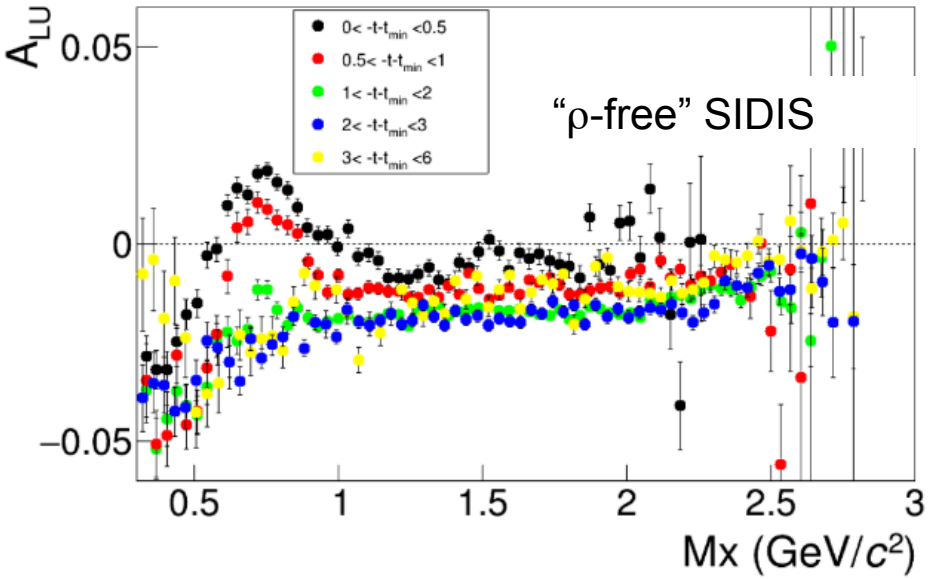
Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





Negative sign of the SSA (plateau) defines the TFR dominance

F. Benmokhtar & Duquesne U.



Major difference only for protons at small t!

With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate

1) kinematical regions (CFR/TFR)
2) dynamical contributions
3) cut on M_X eliminate exclusive VMs

“process” files

Ex. of process files for 3 beam (6.5,7.5,10.6) energies prepared both for MC and data

A data file ex. for exclusive pi+ from RGK 8.477 GeV sample

run#	ev#	λe	λp	P_{e^-}	θ_{e^-}	ϕ_{e^-}	Z_e	P_{π^+}	θ_{π^+}	ϕ_{π^+}	Z_{π^+}
56470	612	-1	0	7.852	0.119	3.270	-4.549	2.578	0.240	6.280	-1.655
56470	677	1	0	5.299	0.159	3.556	-2.241	5.173	0.223	0.045	-2.850
56470	918	1	0	8.107	0.104	2.296	-5.031	1.377	0.903	5.487	-4.998

.....

A data file with 900K rho0s from RGA 10.6 GeV MC sample

generated momenta of all 4 final particles

only written if reconstructed

10040	123	-1	7.476	0.149	3.108	2.655	0.408	5.955	0.173	1.318	6.003	1.254	0.404	1.502										
10040	124	1	7.355	0.104	1.301	1.567	0.532	4.987	1.446	0.048	6.048	1.170	0.771	3.049										
10040	125	1	5.785	0.128	6.227	1.207	0.326	2.578	3.437	0.171	4.464	1.109	0.954	2.155	5.775	0.128	6.218	1.203	0.336	2.580	3.424	0.171	4.466	1.092	0.949	2.151
10040	126	1	8.890	0.103	2.534	1.126	0.482	5.807	0.295	0.884	3.546	1.227	0.706	5.877										
10040	127	1	6.103	0.136	5.827	0.897	0.273	2.349	2.773	0.435	3.689	1.765	0.652	1.085										
10040	128	1	5.412	0.150	3.165	0.435	0.666	0.153	4.712	0.137	0.066	0.979	0.386	3.777										
10040	129	-1	7.030	0.152	1.961	0.470	0.558	0.549	2.308	0.087	6.135	1.731	0.835	4.717										
10040	130	1	7.831	0.177	4.352	1.958	0.263	1.222	0.189	1.556	1.101	1.560	0.636	1.222										
10040	131	-1	4.258	0.162	4.530	1.582	0.391	0.915	4.560	0.098	1.046	1.138	0.892	3.527	4.249	0.161	4.539	1.582	0.393	0.911	4.550	0.098	1.048	1.127	0.864	3.526
10040	132	1	8.817	0.116	4.965	0.670	0.481	3.221	0.395	1.211	0.892	1.657	0.593	1.795										
10040	133	1	4.508	0.187	5.317	4.007	0.134	2.511	1.953	0.138	0.217	1.070	1.013	2.341										
10040	134	-1	8.243	0.109	0.846	0.684	0.184	2.379	1.547	0.608	3.973	1.064	0.276	5.410										
10040	135	1	7.579	0.107	1.815	0.462	0.640	3.245	2.448	0.239	5.088	1.049	0.772	5.556										
10040	136	1	7.811	0.120	3.879	1.152	0.239	2.510	1.413	0.530	0.849	1.162	0.709	6.139										
10040	137	1	3.890	0.250	0.042	4.672	0.134	3.237	1.766	0.165	0.514	1.210	0.914	3.347										
10040	138	-1	3.975	0.209	5.463	5.108	0.210	2.299	1.083	0.452	2.995	1.372	0.722	5.881										
10040	139	1	6.601	0.147	2.629	0.751	0.750	5.989	2.966	0.286	5.718	1.220	0.491	2.808										
10040	140	-1	5.430	0.135	0.173	0.832	0.483	4.146	4.220	0.136	3.445	1.056	0.866	1.485	5.436	0.135	0.173	0.829	0.491	4.121	4.174	0.134	3.479	1.051	0.848	1.479
10040	141	1	9.111	0.091	4.138	0.832	0.970	1.103	0.233	0.837	3.764	1.363	0.319	0.591										
10040	142	1	5.305	0.196	2.851	0.325	0.068	2.061	4.901	0.204	6.167	1.006	0.578	4.773										
10040	143	-1	7.588	0.173	2.488	0.516	0.900	6.020	2.051	0.494	5.403	1.384	0.069	0.913										
10040	144	-1	8.469	0.109	0.749	1.443	0.776	3.773	0.256	0.628	1.197	1.369	0.178	5.260										
10040	145	1	8.395	0.123	5.768	0.995	0.226	1.630	1.015	0.772	2.748	1.133	0.386	3.062										
10040	146	1	5.269	0.201	1.466	0.432	0.317	0.599	4.833	0.214	4.604	1.004	0.412	3.900										

From SFs to HSFs

$$\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}z\,\mathrm{d}\phi_h\,\mathrm{d}P_{h\perp}^2} = \mathcal{K}_{\mathrm{SIDIS}} \sum_{XY} \mathcal{W}_{XY}[F] = \mathcal{K}_{\mathrm{EXC}} \sum_{XY} \mathcal{W}_{XY}[H],, \qquad XY = UU, LU, UL, LL, UT, LT,$$

$$\mathcal{K}_{\mathrm{SIDIS}} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-)}\left(1+\frac{\gamma^2}{2x}\right), \mathcal{K}_{\mathrm{EXC}} = \frac{\alpha y(1-x)}{8\pi^3 x(1-\epsilon)}.$$

proton

photon–proton interference densities H_{mn}^{ij}

photon

$$F_{mn}^{ij}(x, Q^2, z, P_{h\perp}^2) = \frac{Q^2(1-x)}{4\pi^3\alpha}\left(1+\frac{\gamma^2}{2x}\right)^{-1} H_{mn}^{ij}(x, Q^2, z, P_{h\perp}^2).$$

$$\frac{\mathrm{d}\sigma^{\mathrm{excl}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}t\,\mathrm{d}\phi_h} = \mathcal{K}_{\mathrm{EXC}} \sum_{XY} \mathcal{W}_{XY}[\mathcal{H}],, \qquad XY = UU, LU, UL, LL, UT, LT,$$

$$\begin{aligned}\mathcal{W}_{UU} = {} & \tfrac{1}{2}\left(H_{+1,+1}^{++} + H_{+1,+1}^{--}\right) + \epsilon H_{0,0}^{++} \\ & - \sqrt{\epsilon(1+\epsilon)}\cos\phi_h\ \mathrm{Re}\left(H_{+1,0}^{++} + H_{+1,0}^{--}\right) \\ & - \epsilon\cos(2\phi_h)\ \mathrm{Re}\, H_{+1,-1}^{++}.\end{aligned}$$

where in the expressions for $\mathcal{W}_{XY}$ $H_{mn}^{ij}(z, P_{h\perp}^2)\big|_{p'}$ are replaced by $\mathcal{H}_{mn}^{ij}(W, Q^2, t)$, defined as

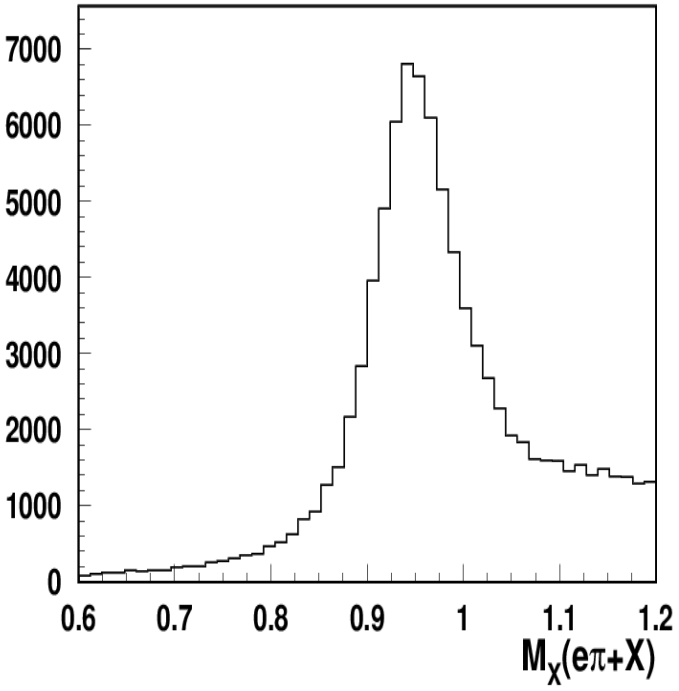
$$H_{mn}^{ij}(z, P_{h\perp}^2)\big|_{p'} = \frac{Q^2}{x}\mathcal{H}_{mn}^{ij}(t_z)\,\delta\left[P_{h\perp}^2 - P_{h\perp,\mathrm{excl}}^2(t_z)\right], \quad t_z = \frac{Q^2}{x}(z-1),$$

$$\begin{aligned}\mathcal{W}_{LL} = {} & S_\parallel \lambda_e \Big[\frac{\sqrt{1-\epsilon^2}}{2}\left(H_{+1,+1}^{++} - H_{+1,+1}^{--}\right) \\ & - \sqrt{\epsilon(1-\epsilon)}\cos\phi_h\ \mathrm{Re}\left(H_{+1,0}^{++} - H_{+1,0}^{--}\right)\Big].\end{aligned}$$

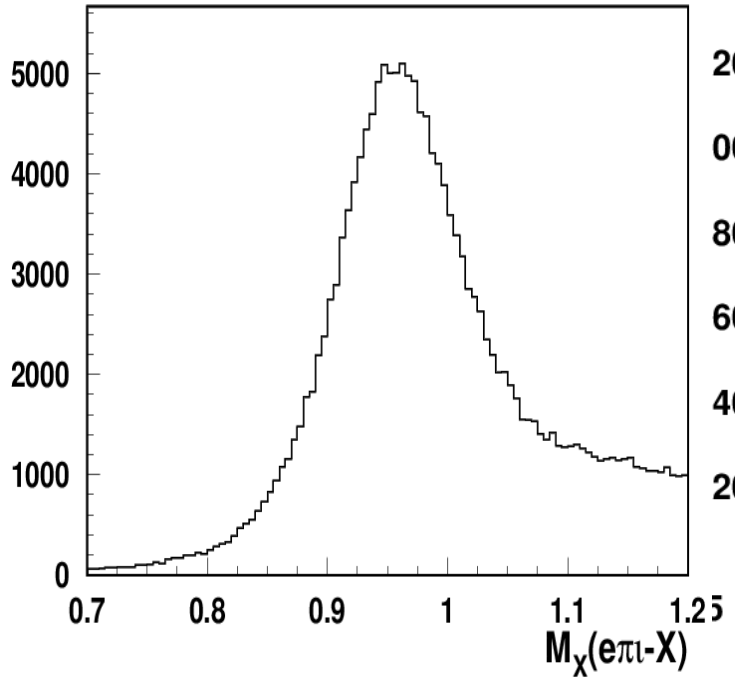
Important to connect processes and write them in terms of HSFs, explicitly containing correlations between unpolarized and polarized measurements

Handling backgrounds

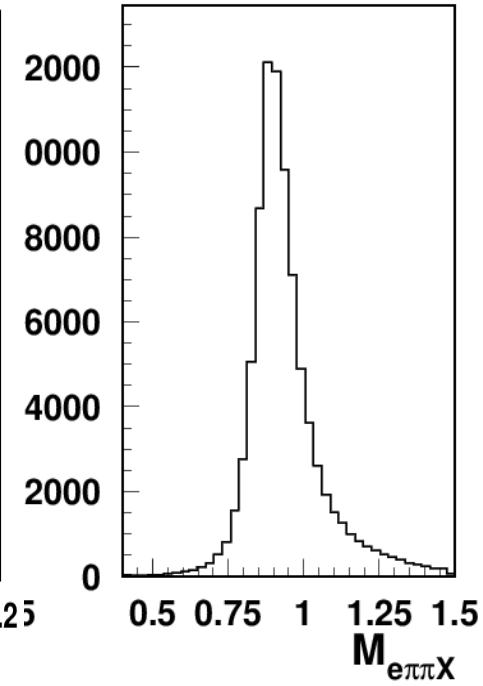
ep->e'π+X(neutron not detected)



en->e'π-X(proton detected)

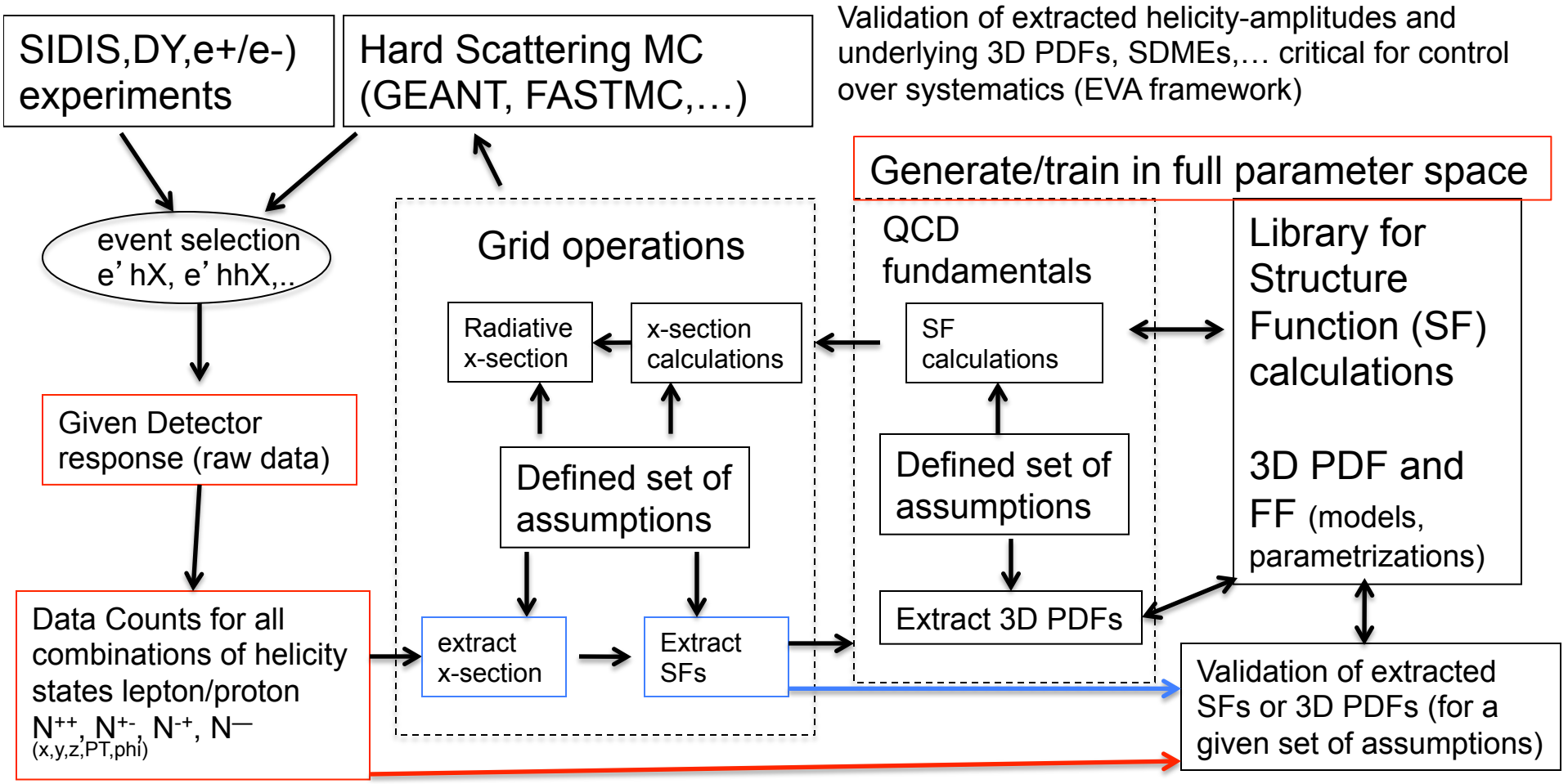


ep->e' $\pi^+\pi^-$X(+protor



More particles detected less backgrounds, but there is always something left, and quantification of impact should be included in the framework

3D PDF Extraction and VAlidation frameworks

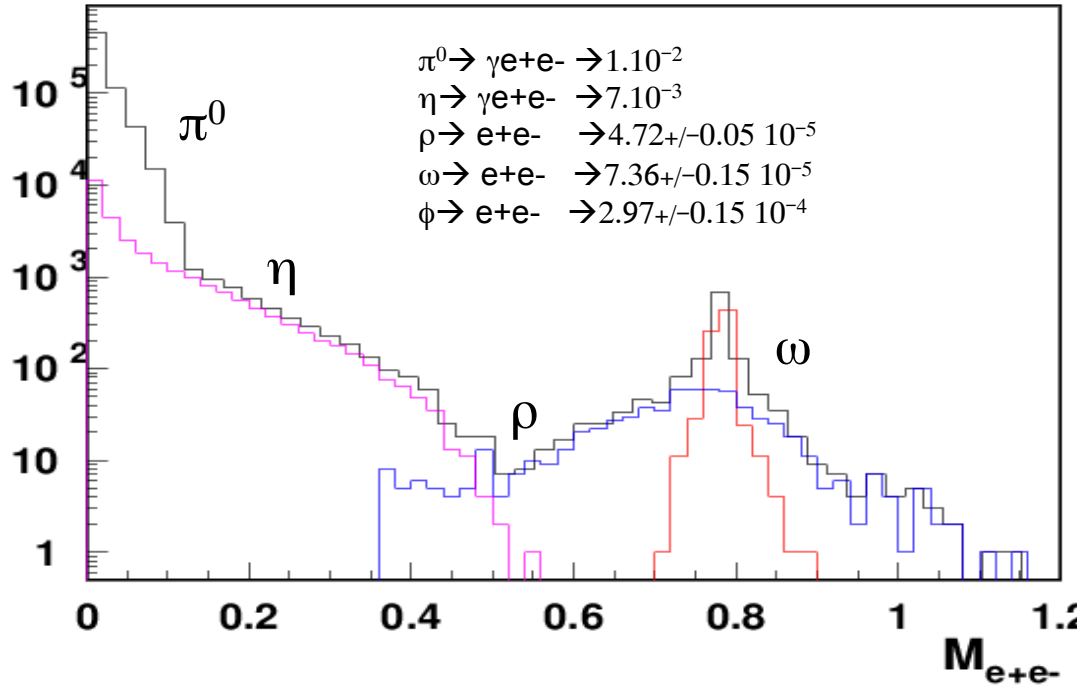


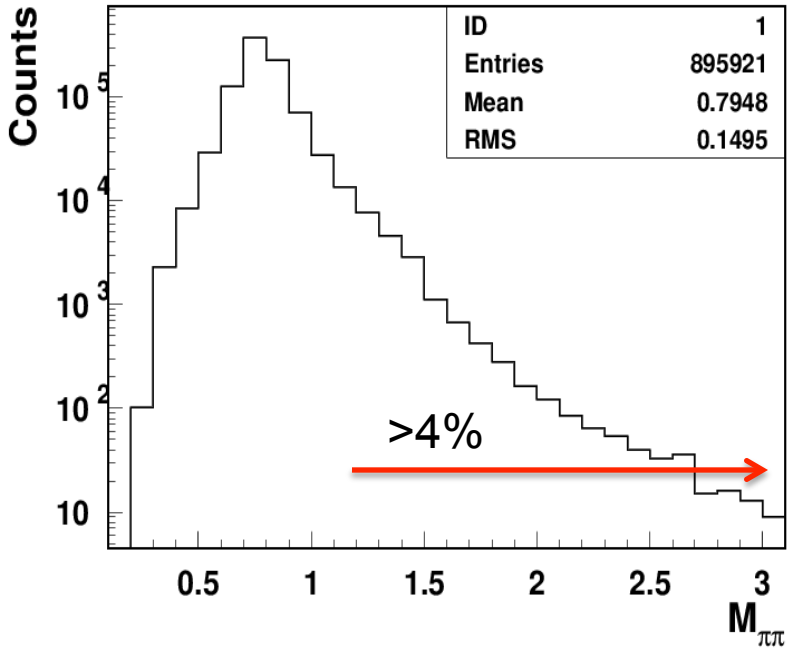
Direct extraction of a given parameter sets from all steps using AI tools for the extraction of 3D PDFs from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing (can be iterative)

Using e+e- to estimate vector mesons

The invariant mass of dihadrons is contaminated by other vector mesons, with shape not changing significantly with hadronization fraction to spin-1 vs spin-0 mesons

decays of π and η are kinematically separeated from ω and ρ^0





VMS are visible in lepton pair production even for Q2>1.
Significant fraction of VM leptonic decays ep→e'e+e-X may affect DY and TCS studies.